

Mirrorcle Technologies MEMS Mirrors – Technical Overview

OVERVIEW

Mirrorcle Technologies Gimbal-less Two-Axis Scanning MEMS Mirror Devices are based on proprietary **ARI-MEMS** fabrication technology initially developed through research projects at the [Adriatic Research Institute \("ARI"\)](#) in Berkeley, CA. They provide very fast optical beam steering across two axes, while requiring ultra-low power. The mirrors deflect laser beams or images to optical scanning angles of up to 32° on each axis. Compared to the large-scale galvanometer-based optical scanners, these devices require several orders of magnitude less driving power: continuous full-speed operation of the electro-static actuators that drive mirror tip-tilt rotation dissipates less than 1 mW of power.

Mirrorcle Technologies MEMS mirrors are made entirely of monolithic single-crystal silicon, resulting in excellent repeatability and reliability. Flat, smooth mirror surfaces are coated with a thin film of metal with high broadband reflectance. Smaller and medium mirror sizes are manufactured as integrated parts of the silicon MEMS chip, while larger mirrors are bonded onto actuators, allowing custom mirror sizes.

HIGH SPEED POINT-TO-POINT TIP/TILT CAPABILITY

Most of Mirrorcle MEMS Mirror device types are designed and optimized for point-to-point optical beam scanning. A steady-state analog actuation voltage results in a steady-state analog angle of rotation of the micromirror. There is a one-to-one correspondence of actuation voltages and resulting angles: it is highly repeatable with no detectable degradation over time. This is in great part due to the electrostatic drive methodology and single-crystal silicon material selection. Positional precision of mechanical tilt in open loop driving of the mirror actuators is at least 14 bits (16384 positions) on each axis. For most devices, with mechanical tilt range of -5° to +5° on each axis, this tilt resolution is within 0.6 milli-degrees or within 10 micro-radians. A sequence of actuation voltages results in a sequence of angles for point-to-point scanning. Mirrorcle Technologies Inc. (MTI) devices can be operated over a very wide bandwidth from dc (they maintain position at constant voltage with nearly zero power consumption at the device) to several thousand Hertz. Such fast and broadband capability allows nearly arbitrary waveforms such as vector graphics, constant velocity line scanning, point-to-point step scanning, object tracking, etc.

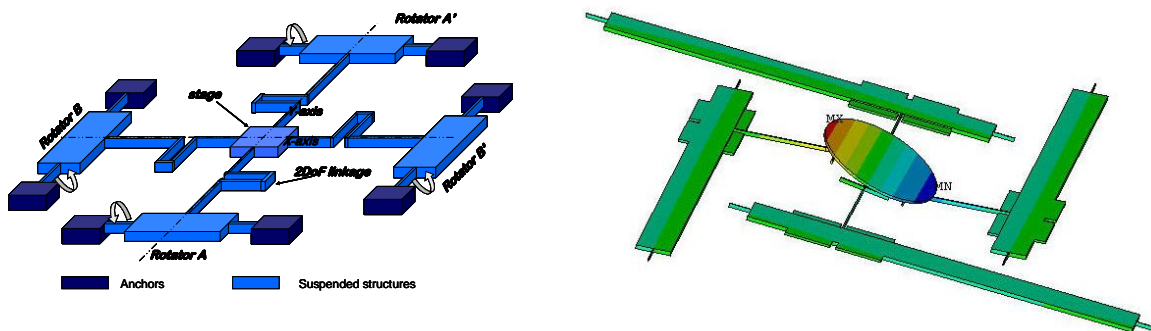


Figure 1. Schematic diagram of a gimbal-less two-axis scanning actuator based on four high aspect ratio rotators connected to the central pedestal by two degrees-of-freedom (2 DoF) linkages.

Multiple awarded patents describe our proprietary **gimbal-less design methodology** and the unique **multi-level beam fabrication methodology** for creating a complete actuator out of one monolithic piece of single crystal silicon. A major advantage of the gimbal-less design is the capability to steer optical beams or images at equally high speeds in both axes. A typical device with a 0.8 mm diameter-sized mirror achieves tilt angles from -6° to +6°, non-resonant optical beam steering of over 1000 rad/s and has first resonant frequency in both axes above 3.6 kHz. Large angle step response settling times of <100 μs have been demonstrated on devices with up to 0.8 mm diameter micromirrors when open-loop driven with specialized input shaping filters.

MULTIPLE SCANNING MODES

MTI devices can also operate in the dynamic, resonant mode. When operated near the resonant frequency, devices give significantly more angle at lower operating voltages and sinusoidal motion. Namely, the MEMS actuators utilize single-crystal silicon springs to support the micromirror and to provide restoring force during actuation. The combination of the springs and the mirror's inertia result in a 2nd order mass-spring system with a relatively high quality factor (Q) of 50-100. Therefore, in this mode, low actuation voltages at frequencies near resonance result in large bi-directional rotation angles. Resonant frequencies are in the range of several kHz.

It is possible to define three modes of operation, as described here and depicted in photos of green laser beam steering in Fig. 2:

- First mode is **point-to-point mode** or **quasi-static mode**. In this case both axes are utilizing the wide bandwidth of operation of the device from dc to some frequency, and not allowing for resonance and ringing. Therefore mirror can hold a dc position, or move in a uniform velocity, or perform vector graphics, etc.
- The second mode is a mixed mode in which one axis is used in **quasi-static mode**, and the other axis is used in **resonant mode**. A typical use case is to run one axis very fast (e.g. few kHz,) to create horizontal lines, and to run the other axis with a sawtooth-like waveform to create a raster pattern that covers a rectangular display or imaging area. Again, the axis operating at resonance should have its parameters carefully obtained, initially at low voltages and angles, to avoid exceeding maximum mechanical angles.
- Third mode is **resonant mode**. In this case both axes are utilizing the narrow, high gain resonance to obtain large angles of deflection and relatively low voltages and high speeds. Motion is limited to very narrowband, sinusoidal trajectories with a phase lag to the applied voltage. It is not necessary to drive the device at the exact resonant peak as the resonant mode can be obtained within few percent of the highest gain point. Resulting 2D motion describes circles, ellipses, and various higher order Lissajous patterns and can be modulated at some rate. Devices designed for point-to-point mode, when driven near and at resonance, easily exceed safe operating angles and break. It is important to approach resonant mode of operation with very small sinusoidal driving voltages about the bias position and very carefully search for a desired operating point and angle, so as not to exceed a given device's maximum mechanical angle limit.

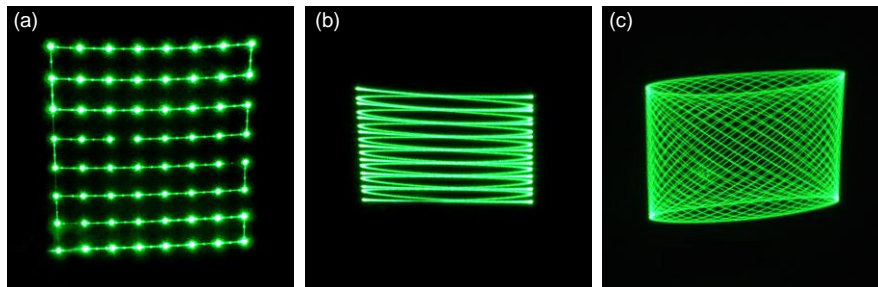


Figure 2. Photographs of examples of using Mirrordle MEMS Mirror in (a) point-to-point scanning mode (quasi-static) on both axes with the laser beam stopping at each angle, then stepping to the next angle, (b) resonant scanning mode on the x-axis (sinusoidal beam motion) and quasi-static on the y-axis (triangle wave motion in this example), and (c) resonant scanning mode on both axes, showing a 2D resonant Lissajous pattern.

MODULAR DESIGN

MTI actuators lend themselves inherently to a modular design approach. Each actuator can utilize electrostatic rotators of arbitrary length, arbitrarily stiff linkages, and arbitrarily positioned mechanical rotation transformers. In addition, the device can have an arbitrarily large mirror diameter. A schematic diagram of the conceptual operation of the gimbal-less 2D designs is shown in Figure 1. Due to this modularity, devices easily lend themselves to customization for a particular application requirement. Depending on the available area/size of the silicon die (in some applications such as bio-medical imaging size is restricted by imaging equipment specs), we can design appropriately sized actuators to obtain maximum performance within allowable parameter space.

Due to this design flexibility and a wide variety of applications that require beam steering, with widely different specifications, we provide many types of gimbal-less two-axis actuator designs. With fourteen major design and manufacturing generations, multiple sub-generations of design tuning for a specific customer or set of specifications, the complete list of working designs has over 60 device types. Most of those device types are available in R&D quantities to give our customers the best chance of quickly finding the best set of parameters and trade-offs for their application development.

SPEED VS. MIRROR SIZE TRADE-OFF

Devices with larger-diameter mirrors are correspondingly slower due to the increased inertia. Inertia of a round mirror is proportional to the fourth power of the radius. Therefore, speed reduces quadratically (square power) with increase of mirror size. This is a general rule for a very rough estimate, but many other parameters affect the actual performance, especially die size and angle swing. An example would be to compare a 0.8mm diameter integrated mirror with a 2.0mm diameter integrated mirror, both having the same silicon die size and both having very similar mechanical tip/tilt angles (-5° to $+5^\circ$). The 0.8mm device's first resonant frequency is $\sim 4\text{kHz}$, while the 1.7mm device's is $\sim 1.1\text{kHz}$.

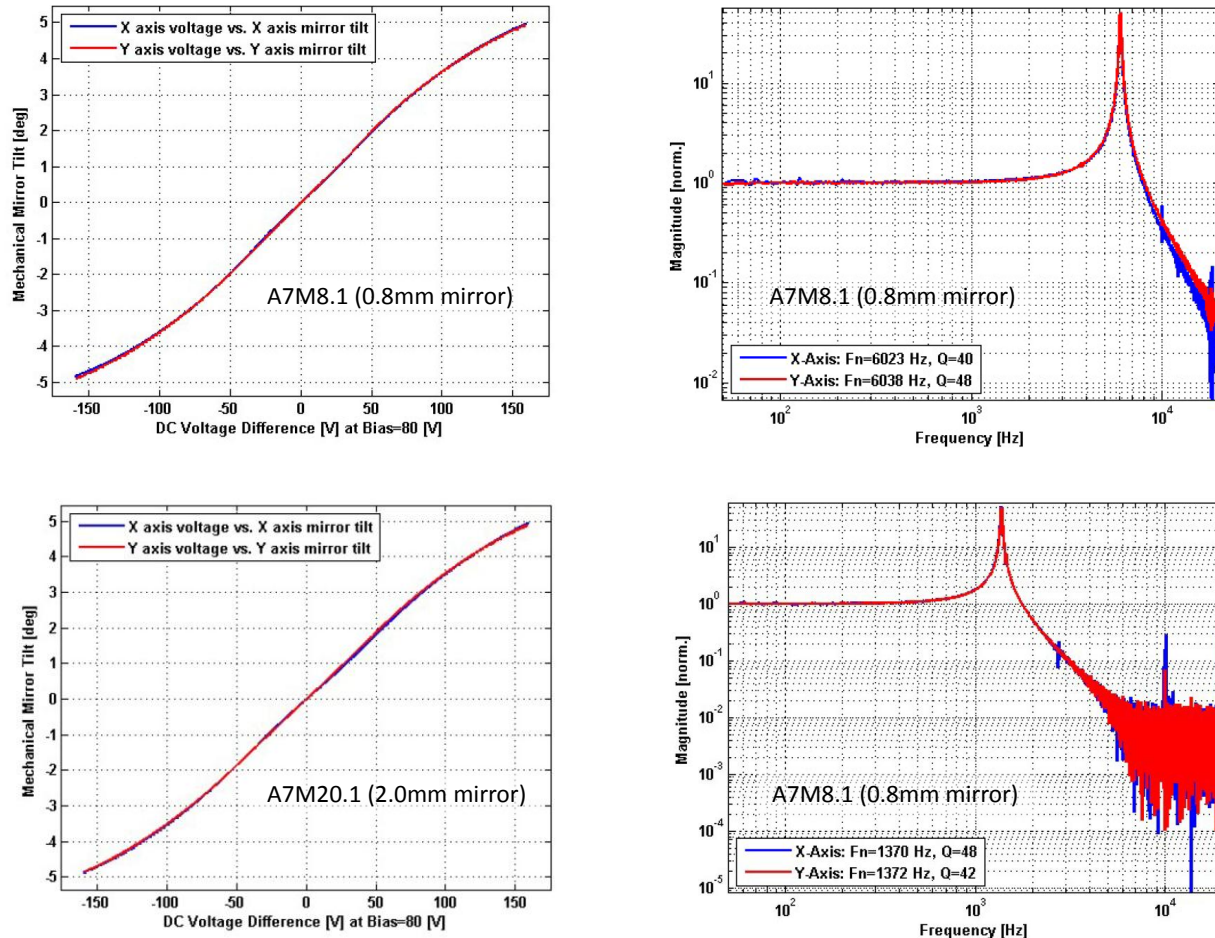


Figure 3. Voltage vs. Angle (static response), and small signal (frequency) response plots of two device examples. (a) and (b) for A7M8.1 device with integrated 0.8mm mirror, and (c) and (d) for A7M20.1 device with integrated 2.0mm mirror.

OPTIMAL ACTUATOR SIZES

Over 70 distinct device types have been designed and manufactured. A very significant design parameter with a strong influence on key performance specifications is actuator (silicon chip) size. Larger actuators provide higher forces and torques for driving larger mirrors at faster speeds, but also cost more to produce and require larger packages. Small actuators are best match for smaller mirrors as the actuators themselves also have smaller inertia. Presently, the in-stock designs fall into 4 size categories:

- 1) 4.23mm x 4.23mm actuator
- 2) 5.20mm x 5.20mm actuator
- 3) 7.25mm x 7.25mm actuator
- 4) 8.00mm x 8.00mm actuator

It is important to look at each specific design to decide for an appropriate match for a certain application and set of specifications. Broadly speaking, mirrors with diameters equal to or larger than 3.0mm should be used with sizes #3 and #4 for best performance, while mirrors with diameters equal to or smaller than 1.2mm should be used with sizes #1 and #2.

FOUR-QUADRANT (4Q) TIP-TILT CAPABILITY

Several years ago when MirrorcleTech's gimbal-less technology was in early stages of development, all devices fabricated in generation ARIMEMS1 through ARIMEMS6 were one-quadrant (1Q), or uni-directional type devices. This refers to the fact that each axis (these are still two-axis or dual-axis or 2D devices) is able to deflect a mirror from rest position (0°) to one side (e.g. 8°), but not to the opposite side (e.g. -8°). So a typical one-quadrant (1Q) device achieves mechanical tilt of 0° to 8° on the X axis and 0° to 8° on the Y axis. More recently, all device types provide four-quadrant (4Q) beam-steering capability which typically allows for overall larger total tip/tilt angles and has additional benefits of linearization, described in the next section.

Figure 4 below provides a graphical explanation as to the difference between the two types of devices. In both examples, device is optically setup such that at 0V actuation, the laser beam is deflected normally to the wall at the origin of the co-ordinate system. Under such conditions, 1Q devices will address points only in the 1st quadrant, while 4Q devices in all four quadrants. Note that the 1Q device can be optically setup to address all 4 quadrants by shifting its non-actuated 0V position left and down so that it is not normal to the wall. The figure also shows typical characterization results for representative devices of each type. Note that negative DC actuation voltage difference in the bi-directional device represents voltage applied to rotators that provide negative rotation, and not actually necessarily negative voltage.

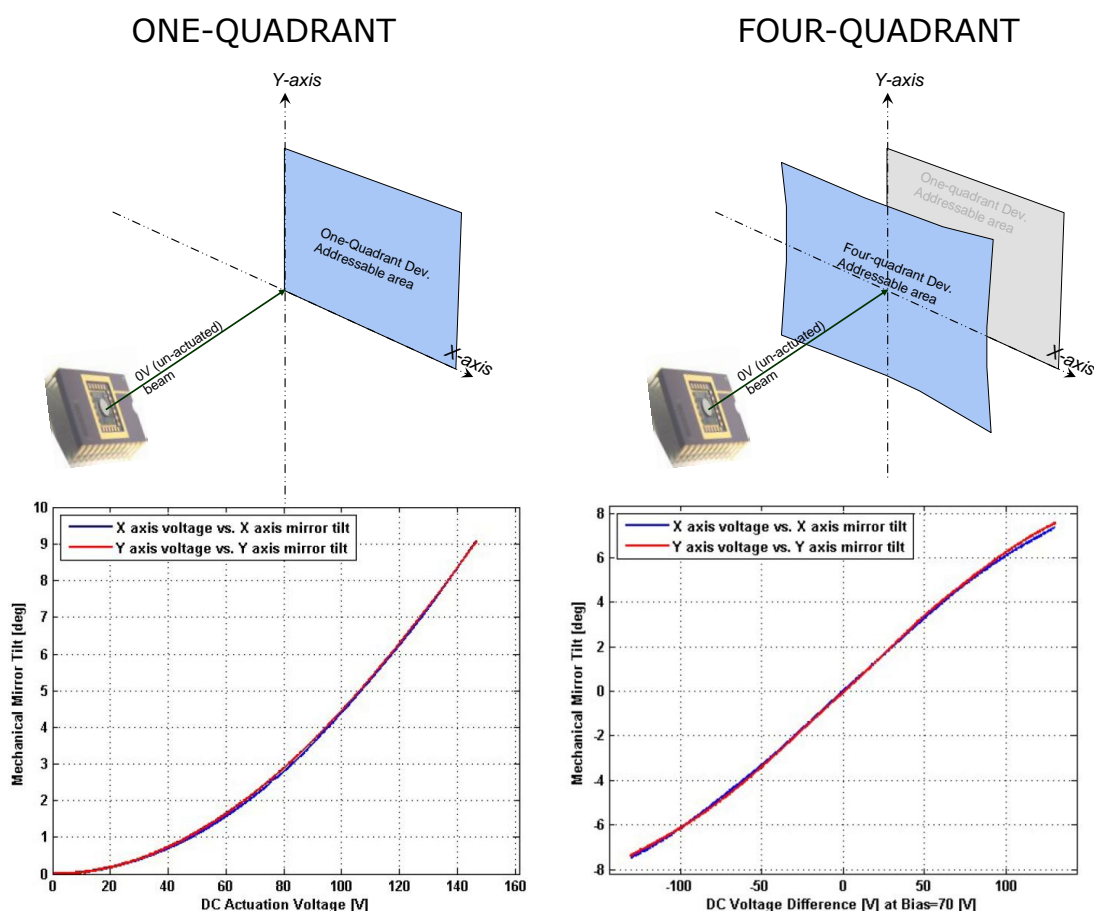


Figure 4. Comparison of addressable angles/areas by uni-directional and bi-directional devices; the representative voltage vs. angle measurement of each.

LINEARIZED DRIVING OF FOUR-QUADRANT (4Q) DEVICES

Mirrorcle Development Kits and OEM MEMS drivers utilize a device-specific method of driving the 4Q MEMS actuators with a Bias-Differential Quad-channel (BDQ) scheme. This scheme linearizes actuators' voltage-angle relationship as seen in Fig. 4 on the right-hand side, and improves smooth transitions from one quadrant to another, i.e. from one actuator to another within the device. In this mode both the positive rotation portion and the negative rotation portion of each rotator are always (differentially) engaged, and therefore the voltages and torques are always continuous. All Mirrorcle MEMS drivers are designed to operate in this mode and therefore have four high-voltage amplifier channels with biased and differential output. Inputs are either digital or analog and only two channels are required to command x-axis and y-axis position.

MIRROR MATERIAL, QUALITY, AND COATING

Mirrorcle Technologies MEMS Mirrors are fabricated out of single-crystal silicon wafers of the same prime grade and quality that is used for the manufacturing of integrated circuits such as PC microprocessors. Because similar mass production processes are utilized to obtain highest manufacturing repeatability, quality, and lowest cost, silicon is used as the base material. The choice of using same starting material as the vast silicon chip industry has further benefits, specific to optical applications. The wafer surfaces and therefore fabricated mirror surfaces are polished to below 1nm roughness with world's best polishing technologies. Also unique to silicon-based microfabrication is the availability of methodologies to make the surfaces ultra-clean prior to mirror metallization. Furthermore, the silicon material is inherently without any residual stress from its manufacturing and maintains this property after mirror microfabrication. Therefore silicon mirrors have extremely high flatness, with curvature often below level measurable with conventional interferometers. As the base material in a MEMS mirror, silicon has the optimal properties of smoothness, cleanliness, and flatness.

In the final manufacturing step for optical beam steering applications, the silicon mirror must be coated for high reflectance at required optical wavelengths. In our standard processes, we coat the silicon mirrors with a thin layer of Aluminum or Gold. All in-stock MEMS mirrors are available in one of those two coating categories. In specialized, research projects, our mirrors have been coated with protected silver, dielectric layers, and MoSi layers for extreme UV applications. In most cases other materials can be used, however it is necessary to find thin and low-stress coatings that would not significantly degrade the mirrors' excellent flatness characteristics. In our standard processes with Al or Au coatings, we maintain >5m radius of curvature in any mirror type and size.

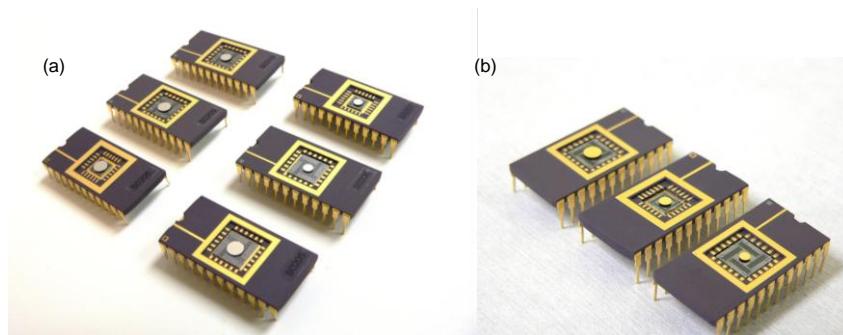


Figure 5. MEMS Mirrors coated with (a) Aluminum, and (b) Gold.

All devices can handle at least 1W of CW optical laser power, regardless of mirror size, laser wavelength, and mirror coating. For higher CW laser power it is important to match the mirror coating choice with the wavelength. Generally, larger mirror sizes can handle higher CW powers due to improved surface cooling. For pulsed lasers with low average power the concern would be different, i.e. potential damage of metal coatings due to high peak power pulses. In those cases Mirrorcle mirrors perform as well as most aluminum or gold-coated mirrors do in traditional optics industry.

MIRROR TYPES AND SIZES

Integrated Mirrors of up to 2.0mm diameter are monolithically fabricated as an integrated part of the gimbal-less actuator device structure. They are the central area of the silicon die and share the same microfabrication steps as the surrounding electrostatic actuators. These mirrors are constructed of the same available silicon layers, featuring nearly perfectly flat and smooth silicon surfaces. On four sides, the mirrors are connected to bi-axial linkages that provide two-axis movement. Since 2015, we continually stock devices with integrated mirrors in the following diameters: 0.8mm, 1.2mm, 2.0mm. In the first quarter of 2016, 1.6mm and 2.4mm diameter were added to this standard availability. All in-stock integrated mirrors are coated with pure Aluminum, which gives high reflectivity across a very wide range of wavelengths. Metallization with Gold can be done on wafer scale, and is therefore available for larger, production orders.

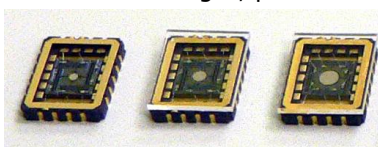


Figure 6. Integrated MEMS Mirrors, three sizes from left to right, 0.8mm, 1.2mm, 1.7mm (Legacy design – replaced by 1.6mm in 2016). 2.0mm and 2.4mm diameter not pictured. Devices up to the 2.0mm dia. are packaged in the LCC20 ceramic package with ~9mm x ~9mm outline. The 2.4mm device is packaged in the LCC28 ceramic package ~11.4mm x ~11.4mm.

Bonded Mirrors are fabricated separately from the silicon actuator structure and are intended for subsequent microassembly on top of devices. Because these mirrors are attached from above the device actuator structure, they do not occupy a part of the actuator area and therefore can be essentially made in arbitrary sizes. The Bonded Mirrors methodology allows users to select the size, as well as the geometry of mirrors for each individual application, in order to optimize the trade-offs between speed, beam size, and scan angle. Mirrors are bonded onto ready-made actuators, providing the ability to economically adapt a small set of fabricated devices for a wide range of applications.

In the past, batch fabrication of silicon devices such as two-axis micromirrors allowed for only one type/size of micromirror as part of the overall device. In order to produce devices with varying mirror sizes, most technologies require not only a new fabrication cycle, but in some cases complete actuator redesign. At Mirrorcle Technologies, we provide a MEMS-based, customizable aperture size beam steering technology for the first time. Namely, sets of electrostatic actuators optimized for speed, angle, area footprint or resonant driving are designed and realized in a self-aligned DRIE fabrication process. Metalized, ultra low-inertia single crystal mirrors stiffened by a backbone of thicker silicon beams are created in a separate fabrication process. The diameter, as well as geometry, of the mirror is selected by our customers, in order to optimize performance for their specific application. Suitable mirrors are subsequently bonded onto adequate actuators. This modular approach allows either the absolute optimization of a device prior to fabrication, or the ability to economically adapt a small set of fabricated devices for a wide range of applications.

We maintain stock of bonded mirror diameters in both aluminum and gold coating in the following sizes: 0.8mm, 1.0mm, 1.2mm, 1.6mm, 2.0mm, 2.4mm, 3.0mm, 3.6mm, 4.2mm and 5.0mm.

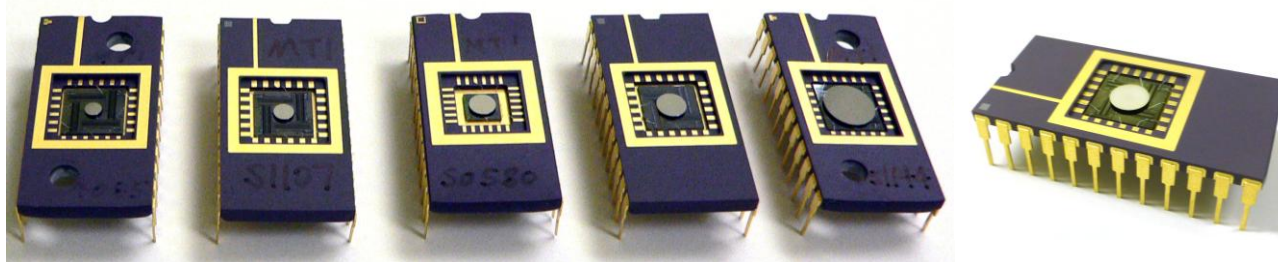


Figure 7. Various MEMS actuators with bonded mirrors of different sizes. Diameters from left to right: 2.0mm, 2.4mm, 3.0mm, 3.6mm, 6.4mm, and 4.2mm. Sizes up to 5.0mm are maintained in stock in aluminum and gold coating. These devices are packaged in the DIP24 ceramic packages, easiest for handling in development.

MIRROR SIZES vs. ANGLE CAPABILITIES

Mirrorcle MEMS Mirrors are not limited in angle regardless of the mirror size, except in few special cases. Maximum angle is typically limited only as a trade-off for maintaining high speed and in most designs that angle is around -5° to $+5^{\circ}$ of mechanical deflection. All integrated mirror sizes and bonded mirrors through 5.0mm diameter all can be utilized in that range. Some Mirrorcle actuators have significantly higher angle capability, and in that case only the 4.2mm mirror is restricted as it has a mechanical throw limit of $\sim 7^{\circ}$ in any direction. In custom R&D projects, Mirrorcle has also demonstrated mirrors of 6.4mm, 8.2mm, and 9.0mm. In those cases, larger mirror inertia was traded off for lower angle throw to maintain high speeds and robustness to shock and vibration. Therefore, in those sizes angles were limited to $\sim -1^{\circ}$ to $+1^{\circ}$ for special applications.

DEVICE PACKAGES AND WINDOWS

Many package options are available with Mirrorcle MEMS mirrors as they do not require any special materials, shapes, or environmental conditions for proper operation. The devices require at least 12 pins and smooth and flat cavities from at least 4.4mm and larger. Other specifications depend on customer requirements, ease of use and optical mounting etc. In R&D quantities, three package options are always available in stock. The traditional, ceramic dual in-line package (DIP) with 24 pins remains the most convenient and versatile option for the majority of R&D scenarios. Those packages, seen in Fig. 8 and Fig. 9a, come in a variety of cavity sizes and can host every Mirrorcle MEMS chip size from 4mm to 8mm square. DIP24 remain the easiest solution in terms of handling as it can be simply held by hand along the ceramic sides, thereby easily avoiding contact with the sensitive MEMS and window area. For DIP24 devices there is also an easy ZIF socket mounting solution, allowing effortless optical bench breadboarding, device swapping, etc.

To take further advantage of the small size of MEMS based beam steering technology, Mirrorcle also offers smaller packages, Leadless Chip Carriers (LCC). The LCCs come in two sizes, 20-pin 9mmx7mm outline LCC20 for integrated mirrors and smaller actuators, and 28-pin 11.5mmx11.5mm outline LCC28 for the larger actuators. Because the size of LCCs is much smaller than DIP24 and practically the whole area is covered by a

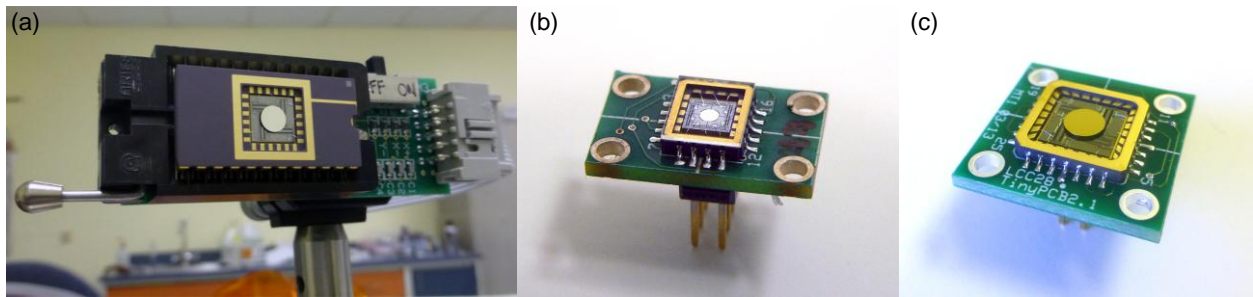


Figure 8. Three package options always in stock for R&D and small volume quantity orders. (a) DIP24 for easiest handling and experimentation with MEMS mirrors, mounting in ZIF socket on optical benches as shown, etc. (b) LCC18 pre-soldered into a TinyPCB with 13mm x 20mm outline and a connector on the back, and (c) LCC28 pre-soldered into a TinyPCB with 20mm x 20mm outline with a connector on the back.

protective window, they are difficult to safely handle and require tweezers and additional care. To make them more user friendly and alleviate the further challenge of soldering them into applications, Mirrorcle's LCC-packaged mirrors are provided soldered onto TinyPCBs, seen in Fig. 9, for easier mounting options for applications with space restrictions. Other custom packages can also be accommodated with an initial NRE for having the proper fixtures made for assembly and testing.

MTI devices are used in a broad variety of laser beam-steering applications, whether in point-to-point (P2P) mode or e.g. raster or vector scans. To protect the high quality optical mirror surface of any contamination or accidental contact, Mirrorcle MEMS are covered by protective windows made of 0.5mm thick optical-quality fused silica substrate. In R&D quantities, and in most production scenarios, those windows are affixed by adhesives and do not hermetically encapsulate the MEMS device as that is not necessary. Their primary role is to prevent direct mechanical contact to sensitive MEMS and prevent particles from entering the cavity. Until 2014, the windows were only available with double-side anti-reflection (AR) coating for visible wavelengths. Due to increasing customer requests at longer wavelengths, MTI now offers windows with broadband AR coatings for two additional ranges, giving the following selection to customers:

Type A 425nm – 675nm double-side AR coating

Type B 650nm – 1100nm double-side AR coating

Type C 1000nm – 1600nm double-side AR coating

For best performance each coating type should be used at as-designed incidence angles ($<30^\circ$) and kept as clean as possible and without any direct contact. As seen in the figure below on the right hand side, custom windows are also offered in production. In those cases even better performance can be obtained by reducing the required bandwidth and thereby further reducing any unwanted reflectance.

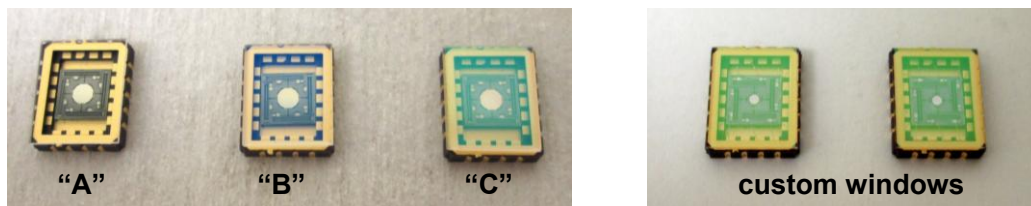


Figure 9. Three anti-reflection (AR) coating types are offered with Mirrorcle MEMS mirrors to cover a wide range of wavelengths in R&D quantities (left). In larger, production quantities, customers' specific incidence angles and wavelengths are taken into consideration and custom coated windows are offered.

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